Confinement of Cosmic Rays in Dark Matter clumps

W. DE BOER[1], V.ZHUKOV[1,2]
[1] *Institut für Experimentelle Kernphysik, Universität Karlsruhe,76128 Karlsruhe, Germany*
[2] *Skobeltsyn Institute of Nuclear Physics, Moscow State University, 119992 Moscow, Russia*
zhukov@physik.uni-karlsruhe.de

Abstract: Some part of the relic Dark Matter is distributed in small-scale clumps which survived structure formation in inflation cosmological scenario. The annihilation of DM inside these clumps is a strong source of stable charged particles which can have a substantial density near the clump core. The streaming of the annihilation products from the clump can enhance irregularities in the galactic magnetic field. This can produce small scale variations in diffusion coefficient affecting propagation of Cosmic Rays.

Introduction

The Cosmic Ray (CR) propagation below 10^{17} eV can be described as a resonant scattering on the magneto hydrodynamic turbulences (MHD) with the scale k equal to the particle Larmor radius r_g in the galactic magnetic field B, $k_r^{-1} \sim r_g = pc/ZeB$ [1]. The MHD turbulences can propagate in space as Alfvén waves with the velocity $v_a \sim B/\sqrt{4\pi\rho_H}$, which depends on the interstellar gas density ρ_H and is in the order of $10^7 cm/s$. The level of MHD turbulences is proportional to the random component of the magnetic field $\delta B/B$ and can be associated with fluctuations in interstellar medium (ISM) which follow a power law $W(k) \propto k^{\alpha-2}$ in the range of $k = 10^{-20} - 10^{-8} cm^{-1}$, where $\alpha = 1/3$ for the Kolmogorov spectrum. The waves interact with the CR and interstellar medium and can be enhanced or damped, depending on the energy flow. In the self consistent approach the kinetic equation for the spectral density $W(r,k)$ of MHD turbulences in spherical coordinates can be written as [1]:

$$\frac{\partial W}{\partial t} + \frac{1}{r^2}\frac{\partial}{\partial r} v_a r^2 W - \frac{\partial v_a}{\partial r}\frac{\partial}{\partial k} kW = (G-S)W \quad (1)$$

The G term describes the enhancement of turbulences due to streaming of CR particles and S represents the damping. The growth of turbulences occurs when the CR streaming velocity v_s is larger than the Alfv́en speed v_a [2]. The growth depends on the gradient of the CR density f which can be obtained from the steady state solution of the diffusion equation (here without convection and reacceleration)[3]:

$$\frac{1}{r^2}\frac{\partial}{\partial r} D \frac{\partial}{\partial r} r^2 f - \frac{\partial}{\partial p}\frac{\partial p}{\partial t} f - \sigma v n_H f = -q(p,r) \quad (2)$$

,where $q(r,p)$ is the source term, $\frac{\partial p}{\partial t}$ energy losses and σ fragmentation cross section. The diffusion coefficient D at resonance is related to $W(k,r)$ as : $D(r) \approx v r_g^2 B^2 / 12\pi W(k_r, r)$ and a high level of turbulences corresponds to the small coefficient and local confinement of particles. Since the enhancement and damping strongly depend on the local environment, this opens a possibility for spatial variations in propagation parameters and therefore CR density. Here we consider how the dark matter (DM) annihilation can introduce such variations and affect the CR propagation.

Dark Matter annihilation in clumps

The N-body cosmological simulations and analytical calculations show that in the inflation scenario the smallest DM structures, or clumps, originate from primordial density fluctuations. These primordial clumps are partially destroyed during evolution contributing to the bulk DM but 0.001-0.1 of total relic DM can still reside in clumps, depending on initial conditions [5]. The clump mass distribution follows $n(M)dM \sim M^{-2}$ with the minimum mass $M_{cl}^{min} \sim 10^{-8} - 10^{-6} M_\odot$ defined by free streaming of DM particles after kinetic decoupling [4]. The local number density

distribution of clumps n_{cl} depends on the bulk density profile and tidal destruction in the galaxy [6]. The clumps density profile is probably cuspy $\rho_{cl} \propto 1/r^{1.5-2.0}$ but is saturated at some critical density ρ_{max} forming a dense core r_c [4]. Inside the clump, the DM of mass m_χ will annihilate producing stable particles: protons, antiprotons, positrons, electrons and gamma rays, which can be observed on top of the ordinary CR fluxes. The luminosity of the clump for an i-component is: $q_i(r,p) \sim \frac{\langle\sigma v\rangle Y_i(p)}{m_\chi^2}\rho_{max}^2 r_c^3$, where Y_i is the yield per annihilation. For most of DM candidates the annihilation goes into fermions, predominantly quark-antiquarks pair. For example the mSUGRA neutralino of $m_\chi = 100$ GeV annihilating in $b\bar{b}$ will produce per annihilation at 1 GeV : ∼3 positrons or electrons, 0.3 protons or antiprotons and 8 gammas, the precise energy spectrum from quarks hadronization is well measured in accelerator experiments. The $\langle\sigma v\rangle$ is the thermally averaged annihilation cross section which can be estimated from the observed relic DM density in time of decoupling ($T_{dec} \sim \frac{m_\chi}{20}$): $\langle\sigma v\rangle \approx (\frac{2\cdot 10^{-27}cm^3s^{-1}}{\Omega_\chi h^2})$, where $\Omega_\chi h^2 = 0.113\pm0.009$ [7]. Nowadays, at lower temperature, the cross section can be the same for the s-waves or only smaller in case of p-waves annihilation channel [9]. The DM annihilation (DMA) signal is decreasing fast with the DM mass, at least as $q \sim m_\chi^{-3}$, but the ρ_{max} is not well known and the significant DMA signal still can be obtained even at large masses of DM particles. Since the primordial clumps are much denser than the bulk component, most of the annihilation signal will come from the core of most abundant smallest clumps. The contribution from clumps is usually expressed as a 'boost factor' $b \sim \frac{F_{clump}}{F_{total}}$ and $b >> 1$, probably except galactic center for the cusped bulk propfile. Taking a clump with $M_{cl} = 10^{-8}M_\odot$ and 100 AU size with the average density of 100 GeV/cm^3, the total yield for GeV charged particles will be $\sim 10^{23}s^{-1}$ for $m_\chi = 100$ GeV. Assuming the isothermal distribution of clumps in the galactic halo of 20 kpc diameter and normalizing at $n_{cl}(8.5kpc) = 10pc^{-3}$, the total luminosity from the DM annihilation in GeV range in 100 years will be $\sim 10^{45}$ particles, to be compared with the SNR explosion delivering $\sim 10^{51}$ particles in the galactic disk. The DM clumps is a compact and constant source of CR and despite of smaller luminosity the local density of produced particles can exceed the galactic average $\langle\rho_{cr}\rangle \sim 10^{-10}cm^{-3}$ producing a gradient in CR density distribution.

MHD turbulences initiated by DM annihilation

The streaming of charged DMA products from the clump with the drift velocity above Alfvén speed can increase the level of local MHD turbulences. The amplification of MHD waves parallel to magnetic field lines can be calculated as [2]:
$G(r,k) \approx \frac{\pi^2 e^2 v_a}{kc^2}\iint dpd\mu v p^2(1-\mu^2)\delta(p|\mu| - \frac{eB}{kc}) \times (\frac{\partial f}{\partial \mu} + \frac{v_a p}{v}\frac{\partial f}{\partial p})$
,where μ is the cosine of scattering angle and $\frac{\partial f}{\partial \mu} \sim \frac{p^2c^2}{4\pi^2e^2W}\frac{\partial f}{\partial r}$ is the anisotropic term of the CR density distribution which can be obtained from integration of diffusion equation (2). The transverse waves are averaged out along propagation path and scattering is not efficient, that is, only turbulences along local field lines will be effectively amplified by streaming. The growth is reduced in dense molecular clouds with $n_H \sim 10 - 10^5 cm^{-3}$ due to ions-neutral friction which dissipates energy as $S_H \sim \frac{1}{2}\langle\sigma_{col}v_a\rangle n_H$, where $\langle\sigma_{col}v\rangle \sim 10^{-9}cm^3s^{-1}$ is the collisional cross section. The collision of opposite waves leads to a nonlinear damping proportional to the level of turbulences $S_{nl} \approx \frac{4\pi v_t W}{B^2 r_g^2} = S_{nl}^0 W$, where v_t is the gas thermal velocity [3]. In the absence of external source of MHD waves the simplified solution of equation (1) and (2) neglecting energy dependencies, can be calculated for the spatial component analytically:

$$W(r) \sim \frac{exp(-g/r - s_H r)}{r^2(C_0 + s_{nl}exp(-g/r - s_H r)/g)} \qquad (3)$$

,where $g \sim \langle\sigma v\rangle Y_{tot}\frac{\rho_{max}^2}{cm_\chi^2}$ is related to the total clump liminosity, $s_H = S_H/v_a$, $s_{nl} = S_{nl}^0/v_a <<$ s_H are the dampings, and C_0 is a normalization factor. In the steady state it will result in fast increase of $W(r)$ near the clump core followed by an exponential decrease due to damping, see Figure 1. The CR density distribution, obtained from solution of equation (2) with the diffusion defined by (3), will follow the $W(r)$ dependency. The source function for spectral density $W(k)$ is cutoff at $k \sim \frac{eB}{m_\chi}$ but can be extended to smaller wave numbers by collisions, reproducing Kolmogorov spectrum. More detailed consideration would in-

clude energy losses, fragmentation and interplay between electrons and protons streaming which is out of the scope of present paper. For the stable growth the velocity of the clump proper motion and the convection speed should be below local v_a. In this case the anisotropic streaming of DMA products can create a region around the clump with small diffusion $D_{cl} < D_{ext}$, aligned with the local B field and with size defined by the DM density in the clump, annihilation yields and dumping rates. The growth will be strongly suppressed inside dense gas clouds although particles produced in the cusp of the clump or on the border of the cloud still can be confined. The energy losses and fragmentaion in the confinement region r_{cf} can modify spectra of annihilation products. The time scale for the energy losses $\tau_{loss}(E)$ has to be compared with the confinemnt time $\tau_{cf} \sim r_{cf}^2/6D_{cl}(E)$. The DMA antiprotons(protons) will lose energy in the gas clouds by ionization below 100 MeV and by nuclear interactions at higher energies. For positrons(electrons) the synchrotron and inverse Compton are the dominant losses at high and the bremsstrahlung at low energies. The modification of the energy spectra from the clump due to losses is shown in Figure 2 for different diffusion coefficients. Thus the contribution of charged DMA products to the locally observed CR fluxes will depend upon local environments and location of nearest clumps.

Gamma rays from the DM clump will have two components, see Figure 3 where gamma rays have been calculated with the GALPROP code [8] modified to include DMA and small scale variations in propagation parameters. First, the direct gamma rays from DMA $\chi\chi \rightarrow \gamma + X$ will produce a bump in the spectrum at $E \sim 0.1 m_\chi$ independent on the confinement [9] . Second, the electrons(positrons) will contribute to the lower energy gamma rays via bremsstrahlung and inverse Compton, and protons(antiprotons) to the π^0 peak but with somewhat harder spectrum as compare with the gamma rays from CR. The synchrotron radiation of electrons and positrons will also contribute to the radio waves. This can be an important source of radio emission in the galactic halo where the MHD enhancement can result in $\delta B/B > 1$. The secondary contributions will strongly depend on the MHD enhancement and environments: gas

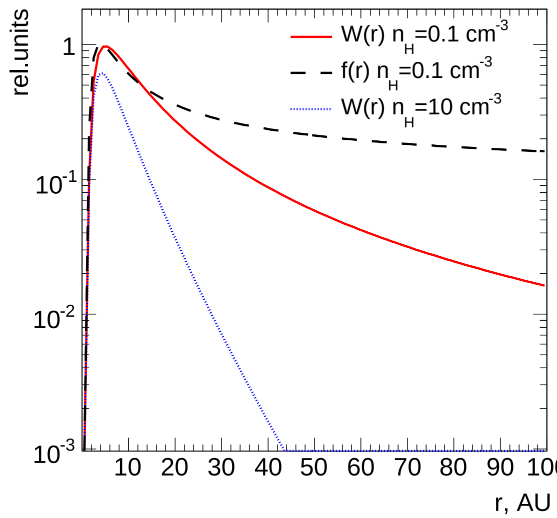

Figure 1: The normalized $W(r)$ and the $f(r)$ density of GeV protons in the DM clump ($\rho_{max} \sim 10^3 GeV/cm^3, m_\chi = 100GeV, v_a \sim 10^6 cm/s, B \sim 1\mu G$)

clouds, low density regions in the galactic disk or the galactic halo. The spectral features of the gamma DMA signal can be distinguished from the diffusive gamma rays produced by ordinary CR [10].

The confinement regions will also affect propagation of the galactic CR. The low energy external CR will not penetrate deep inside such a clump, their contribution will be suppressed while the contribution of DMA particles produced in the clump will be enhanced.

Conclusion

The streaming of charged particles from DM annihilation in the cuspy DM clump can locally enhance level of MHD turbulences reducing the local diffusion coefficient by orders of magnitude. The size of confinement region depends on the luminosity of the clump and damping of turbulences in dense gas clouds. The confinement regions will contribute to the small scale variations of propagation parameters and therefore CR density. The gamma rays from the DM annihilation in

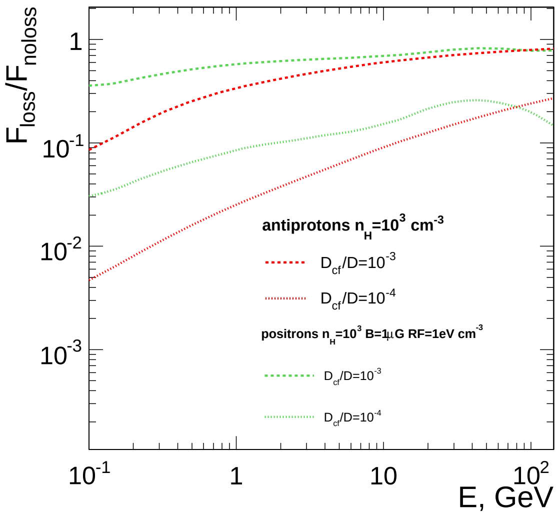

Figure 2: Modified by energy looses spectra of antiprotons and positrons from a clump($r_{cf} = 10^{-2}pc$) at different D_{cl}/D_{ext}.

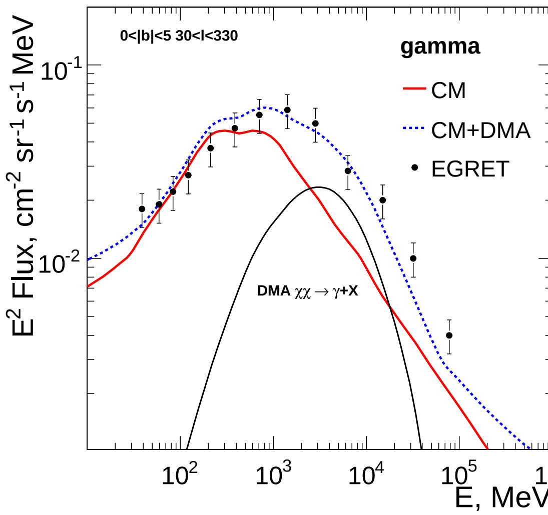

Figure 3: Diffusive spectrum of gamma rays from CR in conventional model(CM) [8] and the contribution from DMA ($m_\chi = 70GeV$).

the clump can be observed as a point like source with a particular spectrum with the bump from the direct gamma production in DM annihilation and secondary gamma rays produced by the confined charged particles in the clump. The annihilation in DM clumps will also produce synchrotron radiation even far away from the galactic disk. The contribution of charged DMA products to the observed CR fluxes will depend on the local environment and can be modified by energy losses. This can change relations between gamma rays and charged components from DMA.

Acknowledgments

The authors thanks H.J. Völk, V.S. Ptuskin, V. I. Dokuchaev, I.V. Moskalenko, A.W. Strong and P. Blasi for useful discussions.

References

[1] R. Kulsrud and W. P. Pearce. *Astroph. J*, 156:445, 1969.

[2] D. G. Wentzel. *ARA&A*, 12:71, 1974.

[3] V. S. Berezinskii, S. V. Bulanov, V. A. Dogiel, and V. S. Ptuskin. *Astrophysics of cosmic rays*. Amsterdam: North-Holland, 1990.

[4] A. V. Gurevich, K. P. Zybin, and V. A. Sirota. *Sov. Phys. Usp.*, 167:913, 1997.

[5] T. Goerdt, O. Y. Gnedin, B. Moore, J. Diemand, and J. Stadel. *MNRAS*, 375:191, 2007.

[6] V. Berezinsky, V. Dokuchaev, and Y. Eroshenko. *Phys. Rev. D*, 68(10):103003, 2003.

[7] D. N. Spergel and et al. *Astroph. J. Supp.*, 148:175, 2003.

[8] I. V. Moskalenko, A. W. Strong, 0. Reimer. *Astroph. J*, 613:962, 2004.

[9] W. de Boer, C. Sander, V. Zhukov, A. V. Gladyshev, and D. I. Kazakov. *Phys. Rev. Lett.*, 95(20):209001, 2005.

[10] W. de Boer, C. Sander, V. Zhukov, A. V. Gladyshev, and D. I. Kazakov. *Astron. Astrophys.*, 444:51, 2005.